Institute of Paper Science and Technology
Atlanta, Georgia

IPST Technical Paper Series Number 664

True Flotation and Physical Entrapment: The Mechanisms of Fiber Loss in Flotation Deinking

Y. Deng and M. Abazeri

July 1997

Submitted to
Nordic Pulp and Paper Research Journal

INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY PURPOSE AND MISSIONS

The Institute of Paper Science and Technology is a unique organization whose charitable, educational, and scientific purpose evolves from the singular relationship between the Institute and the pulp and paper industry which has existed since 1929. The purpose of the Institute is fulfilled through three missions, which are:

- to provide high quality students with a multidisciplinary graduate educational experience which is of the highest standard of excellence recognized by the national academic community and which enables them to perform to their maximum potential in a society with a technological base; and
- to sustain an international position of leadership in dynamic scientific research which is participated in by both students and faculty and which is focused on areas of significance to the pulp and paper industry; and
- to contribute to the economic and technical well-being of the nation through innovative educational, informational, and technical services.

ACCREDITATION

The Institute of Paper Science and Technology is accredited by the Commission on Colleges of the Southern Association of Colleges and Schools to award the Master of Science and Doctor of Philosophy degrees.

TRUE FLOTATION AND PHYSICAL ENTRAPMENT: THE MECHANISMS OF FIBER LOSS IN FLOTATION DEINKING

Yulin Deng and Marcos Abazeri, Institute of Paper Science and Technology

Keywords: Flotation deinking, fiber loss, true flotation, entrapment, froth.

SUMMARY: The mechanisms of fiber loss in flotation deinking were studied using fibers with the same geometry but different surface hydrophobicities. The fiber loss was directly compared with the contact angle of fibers in the pulps. It was found that both true flotation and physical entrapment will contribute to the fiber loss, but physical entrapment is the major contributor. Fiber geometry and froth structure will significantly affect the physical entrapment. Only part of the entrapped fibers can be washed away from the froth during water drainage. To reduce fiber loss in flotation deinking, effective control of foam structure and stability is very important.

ADDRESS OF THE AUTHORS: Institute of Paper Science and Technology, 500 10th Street, N.W., Atlanta, GA 30318, USA.

The flotation technique has been widely used for more than a century in the mineral processing industry, and it has become one of the most effective ink separation techniques in the paper industry. However, the fiber loss in flotation is high, and the fundamentals of fiber floating have not been well understood. The reported fiber loss across most recycled flotation deinking mills is between 5-12% of the gray stock, in which about 50% is high quality fibers. It is clear that brightness Fig.s without any information on the yield of the deinked fibers have only limited value because the achieved brightness strongly depends on the yield.

Although fiber loss is one of the biggest problems in flotation deinking, the mechanism of fiber loss has been an augur. Many authors (Turvey, 1987,1993; Li and

Muvundamina, 1994, 1995) believed that air bubbles routinely adhere to the fibers during the flotation process. In a series of studies on fiber loss in flotation deinking, Turvey (Turvey, 1987,1993) indicated that 1) unprinted fibers do not float; 2) calcium ions can significantly increase fiber loss for printed fibers; 3) nonionic fatty alcohol ethoxylate surfactants cause high fiber loss; and 4) pH plays an insignificant role in fiber loss. From these studies, Turvey (Turvey, 1993) further concluded that fiber loss is due to the fact that part of the fiber becomes hydrophobic and adheres to air bubbles. However, no direct experimental measurement of fiber surface chemistry can support this assumption. Furthermore, some of the conclusions from Turvey (Turvey, 1993) have been argued. For example, many researchers indicated that hydrophobic fibers, even very clean bleached fibers, can still float (Li and Muvundamina, 1994; Dorris and Page, 1997; Ajersch and Pelton, 1992) during the flotation deinking process.

Another explanation for the fiber floating in the flotation cell was given by Li and Muvundamina (Li and Muvundamina, 1995, 1994). In their studies, it was found that long fibers float more easily than fines. To explain this phenomenon they assumed that surfactant molecules have different orientations on the fine and fiber surfaces. Because of the difference in the hydrophobicity between long fibers and fines, the orientation of surfactant on fibers and fines is different. They further suggested that, on the surface of hydrophobic fines, the hydrophobic tails of surfactant molecules anchor onto the hydrophobic sites of fines and leave the charged heads (or hydrophilic parts) toward the water phase. This leads to an increase of hydrophilicity of the surface of wood fines and prevents them from adhering onto air bubble surfaces. For long fibers, on the other hand, the surface is very hydrophilic, and surfactant adsorption is through the interaction between the hydroxyl groups of fiber surfaces and the charged heads of surfactant molecules (or hydrophilic parts of nonionic surfactant), resulting in an increase of hydrophobicity. Li and Muvundamina (Li and Muvundamina, 1995, 1994) believed that the increase of hydrophobicity of fiber surfaces by surfactant adsorption is the main reason for fiber removal. Once again, this is only an assumption, and there is no direct experimental measurement to support it. It will be seen from this study that Li and Muvundamina's assumption is incorrect.

The fiber loss caused by air bubble-fiber adhesion has been questioned in several recent publications (Dorris and Page, 1997; Ajersch and Pelton, 1992, 1993, 1996) In these studies, the authors indicated that the hydrophobicity of a fiber surface does not contribute to the fiber loss, and fiber loss is solely due to the mechanical entrapment of fibers in the froth. This conclusion is based on the fact that fiber loss has a liner relationship with water loss, and the intercept of the plot of fiber loss against water loss is zero. However, this conclusion should also be questioned because the water loss used in these plots was obtained at a fixed froth height but different flotation times, and the plot of the fiber loss against water loss is equivalent to the plot of fiber loss against flotation time. Obviously, it is inevitable to see a zero intercept for the plot of solid removal versus water loss regardless of whether solid removal is caused by true flotation or physical entrapment because the flotation has not started at the zero water loss point. Even for a plot of ink removal (rather than fiber removal) versus water loss measured at different time, a zero intercept will also be expected. This suggests that the zero intercept of fiber loss versus water loss measured at different times will not give any useful information about the fiber loss mechanism.

Although fiber loss in flotation deinking has been studied by many researchers, direct measurement of fiber surface hydrophobicity in flotation cells has not been conducted. In this research program, the fiber surface chemistry in the flotation liquid was directly measured, and the relationship between fiber hydrophilicity and fiber loss in flotation process was studied.

Experimental

Both unsized and AKD (alkyl ketene dimer) sized bleached softwood fibers were used in this study. The average fiber length is 2.83 mm. Because sized fibers have the same geometric property as unsized fibers, the contribution of fiber surface chemistry and fiber length to the total fiber loss can be separately studied. The sized fibers were made by the reaction of fibers with varying amounts of a cationic AKD sizing emulsion (Hercon 70, Hercules Inc.) in ~3% fiber consistency for 5 minutes. The furnishes were filtered and air dried for 2 hours. The air-dried fibers were then heated to 100°C in a vacuum oven for ~30 minutes.

Surfactant, Triton X-100 (TX-100, analyze grade, J.T. Backer Inc.), was used as received.

A dynamic contact angle analyzer (Cahn DCA 312) was used to measure the surface tension of liquid and the dynamic contact angle of liquid on individual fibers. The technique for measuring the dynamic contact angle of aqueous solution on a group of separated fibers was developed in our laboratory (Deng and Abazeri) The dynamic wetting force on the fibers was measured by an electronic microbalance (0.1-mg resolution) and analyzed by a computer using DCA software. A zero-receding contact angle for all of the fibers (sized and unsized) in water and TX-100 solutions was found in our previous study (Deng and Abazeri). The physical properties of fibers used in this study are given in **Table 1**.

The flotation cell used in this study is schematically shown in **Fig. 1**. The flotation unit includes a polyacrylate column (12 cm in diameter; variable in height) and an air inlet filter. Two types of air inlet filters with pore sizes of 10 or 2μm were used. Nitrogen was blown into the pulp at a required rate through the air inlet filter. The ultra-high pure (UHP) nitrogen was run through a digital flowmeter (Fisher product) before the flotation cell. The flow rate was first adjusted to a required value before the flotation experiment. The foam that spilled over the column was collected, and weighed, and the water loss was calculated. Both removed and residue fibers were then filtered, oven dried, and weighed.

A significant different from previous studied (Dorris and Page, 1997; Ajersch and Pelton, 1996) is that the water loss obtained in this study was controlled by adding extra columns to the top of the flotation cell at a fixed flotation time, i.e., the water loss is a function of froth height rather than flotation time. As a result, the water drainage time in the froth phase was increased when the froth height was increased, resulting in a decrease in the water loss.

Results and discussion

Effects of bubble size and surfactant concentration on the water loss

In the flotation process, the void volume between air bubbles in the froth phase will be filled up by water and solid suspensions. As a result, the overflow of the foam carries parts of solid materials out of the flotation cell. The amount of solids removed from the flotation process by physical entrapment is a function of water removal. Obviously, the structure and height of the froth will significantly affect the water loss, therefore, the solid removal. **Fig. 2** shows the water loss as a function of the froth height obtained using 10- and 2-μm air inlet filters, respectively.

It can be seen that the water loss decreases as the froth height increases. This happens because when the froth raises up in the flotation cell, part of the entrapped water in the froth network drains back to the pulp. The drainage rate of entrapped water depends on many factors, such as the froth structure, bubble size, air flow rate, surfactant concentration, fluid dynamic properties of liquid between bubbles, etc. However, if other parameters remain a constant, the water loss should depend on the air bubble size. **Fig. 2** clearly shows that the 2-μm air inlet filter gives much higher water loss than the 10-μm filter. This is consistent with the geometric consideration of void volume between air bubbles, i.e., the smaller the air bubbles, the larger the void volume. The higher water loss caused by smaller bubbles should also affect the fiber loss and ink removal because more fibers and ink particles may be entrained in the froth network. The effects of air bubble size on the fiber entrapment will be discussed later.

Fig. 3 shows that, as other parameters remain a constant, water loss increases with an increase in surfactant concentration. This is because that as the concentration of surfactant increases, the surface tension of the solution decreases, resulting in a decrease in the bubble size and water drainage rate in the froth. However, it is surprising that the water loss continually increases with surfactant concentrations up to ~400 mg/L, which is far above the critical micellization concentration of TX-100 (CMC, 195 mg/L). It has been well-known that both the free surfactant concentration and the surface tension of the solution are constant, and there should not be any change in bubble size and froth structure at the surfactant concentration above the CMC. Obviously, the continued increase in water loss at the concentration above the CMC cannot be explained as the increase in air bubble stability or decrease in bubble size at equilibrium conditions. We believe that the dynamics of surfactant adsorption on air bubble surface and the fluid dynamics of liquid in the froth microchannels at high surfactant solution are two important factors affecting the water loss at different surfactant concentrations.

Effect of fiber hydrophobicity on the fiber loss

The flotation of solid materials can be divided into "true flotation" and "entrapment." True flotation occurs when solids attach to air bubbles and are floated with them. A basic requirement for true flotation is that the solid particles must be hydrophobic enough so that they can strongly adhere onto the bubble surface. However, entrapment occurs when particles enter the froth with the water and occupy the spaces between the bubbles. When froth raises up, part of the water and particles entrapped in the froth will drain back into the pulp, but the remainder is carried upwards and scraped off. As a result, fiber removal by physical entrapment should be a function of water removal, and at ideal conditions, a linear relationship between fiber removal and water removal is expected. The contributions of true flotation and entrapment in mineral flotation have been discussed, and the following equation has been suggested (Warren, 1985):

$$R = A + CV_{\text{water}} \qquad (1)$$

where R is the total recovery of the given solid suspension at experimental conditions; A is the recovery of the solid by true flotation; C is the concentration of entrapped solids in removed water; and V_{water} is the volume of removed water. At ideal conditions, the true flotation A and the concentration C of entrapped solids in removed water can be obtained from the intercept and the slope of removed solids versus removed water, respectively.

In order to separately study the true flotation and entrapment of fibers in flotation deinking, bleached softwood pulp was first used in this study. Direct measurement of wettability using a separated fiber group technique (Deng and Abazeri) indicated that the receding and advancing contact angles of these bleached softwood fibers in a 100-mg/L TX-100 solution are zero and <5 degrees, respectively (see **Table 1**). This suggests that these bleached softwood fibers are very hydrophilic in this solution and they cannot adhere to air bubbles by hydrophobic force in the flotation process. In other words, the loss of these full hydrophilic fibers in the flotation cell should be caused solely by the physical entrapment.

Fig. 4 shows fiber loss as a function of water loss for different fibers after a 2-minute flotation. According to **Equation (1)** and the contact angle measurement, a zero intercept of fiber loss against water loss should be expected for hydrophilic unsized fibers because all floated fibers in this system are solely caused by physical entrapment. However, the results of **Fig. 4** clearly show that both the slope and intercept for bleached softwood fibers (unsized) are not zero, although the fibers have a zero receding contact angle and <5 degree of advancing contact angle in this solution. This strongly indicates that **Equation (1),** which has been used for the mineral flotation system, cannot be directly used to describe the fiber loss in flotation deinking. It should be noted that **Equation (1)** is based on the assumption that the concentration of entrapped solid concentration (rather than adhered) in the froth phase is a constant which does not change during the water drainage, and all entrapped solid particles will be washed back to the pulp phase if the water is fully drained from the froth. This may be almost true if entrapped particles have a small size and high density, such as mineral particles, but it is not the case for wood fibers because some entrapped fibers cannot pass through the microchannels between bubbles during the drainage of water in the froth phase due to their large size and small density. As a result, a nonzero intercept of fiber loss plotting water loss must be obtained even though the flotation of wood fibers is solely caused by entrapment. Because some of entrapped fibers cannot be washed away during water drainage, a correction for these "unwashable" entrapped fibers must be made in order to use **Equation (1)** for the description of fiber loss in flotation deinking. It should be noted that unwashable entrapped fibers are different from true flotation fibers, although both of them cannot be washed away during water drainage. Obviously, the consistency of these "unwashable" entrapped fibers in the froth should be a function of foam structure, fluid dynamics of water in the froth microchannels, the fiber length and orientation, etc. If all experimental conditions remain a constant during the foam raising up in the flotation cell, it can be approximately assumed that the weight of unwashable entrapped fibers is a constant in the froth. Therefore, **Equation (1)** should be modified to

$$R = A + B + CV_{\text{water}} \tag{2}$$

where B is the weight of unwashable entrapped fibers.

Equation (2) indicates that the intercept of the plot of total fiber loss R versus water removal should equal to the sum of the fiber loss caused by true flotation and unwashable entrapment, $A+B$, rather than true flotation A alone, and this intercept is independent of total removed water V_{water} at a fixed flotation time. **Equation (2)** also indicates that although the true flotation A is zero for full hydrophilic wood fibers, the intercept of the plot of total fiber loss versus water loss should equal to B rather than zero. By plotting total fiber loss against water removal for unsized fibers shown in **Fig. 4**, the weight of "unwashable" entrapped fiber B and the consistency of "washable" entrapped fiber C were 0.29 g and 8.0×10^{-4} g/ml, respectively.

The contribution of hydrophobicity of fiber surface to the fiber loss was studied using AKD sized bleached softwood fibers, and the results are also shown in **Fig. 4.** From **Table 1,** it can be seen that the advancing contact angles for 0.2 and 0.6% AKD sized fibers in a 100-mg/L TX-100 surfactant solution are 28 and 39 degree, respectively, which are much higher than that of unsized fibers (<5 degree) in the same solution. From **Fig. 4,** it can be seen that the fiber losses of sized fibers are consistently higher than unsized fibers. This result indicates that the fiber surface chemistry will also contribute to the fiber loss. Because both sized and unsized fibers used in this study have the same geometric properties, it is reasonable to assume that the entrapment factors B and C in **Equation (2)** are the same for all of the sized and unsized fibers. Therefore, the difference in the fiber loss between unsized and sized fibers is attributed solely to the true flotation A. Although this assumption may be too simple, the experimental results of **Fig. 4** indicate that the slope C is almost a constant for all of the three fibers.

In terms of the above assumption, by applying $B = 0.29$ g and $C = 8.0 \times 10^{-4}$ g/ml to **Equation (2)**, the weights of true flotation A for 0.2 and 0.6% AKD sized fibers were obtained and they are 0.025 and 0.15 g, respectively. Comparing the value of true flotation A with total entrapped fibers $B + CV_{water}$, it can be found that true flotation A is smaller than total entrapped fibers even for highly sized fibers.

In order to further discuss the contribution of true flotation to the total fiber loss, a true flotation fraction F is defined as

$$F = A/R \tag{3}$$

The plots of F as a function of froth height and fiber loss are shown in **Fig.s 5** and **6,** respectively.

It can be seen from **Fig. 5** that the true flotation fraction F for 0.2 and 0.6% AKD sized fibers is in the range of 8-12 and 25-33%, respectively, which depends on the froth heights. The results suggest that although true flotation is one of the mechanisms of fiber loss, most lost fibers (>88% for 0.2% AKD sized and >33% for 0.6% AKD sized fibers) in flotation deinking are mainly attributed to physical entrapment. **Fig. 5** also shows that the true flotation factor F increases as the froth height is increased. This is because the total fiber loss R is decreased, but the true flotation factor A remains a constant when froth height is increased. It can be seen that the total fiber loss can be reduced by ~2-3% (based on total fibers in the flotation cell) when froth height increases from 5 to 125 cm (corresponding to a water loss from ~ 80 to 280 ml) for all types of fibers. This decrease in the total fiber loss is because some entrapped fibers will be washed away from the froth by drained water. Because an increase in the froth height leads to a reduction in the water loss and fiber entrapment but does not significantly affect the true flotation, the true flotation fraction decreases as total water loss is increased. This is shown in **Fig. 6**.

Although water loss in flotation deinking has not been thought of as a problem in the paper mill, the energy saved by reducing water loss can also benefit the paper industry. Even for a fully closed flotation deinking mill, water loss by froth removal can still be as high as 10% of the total water in the flotation cell, which corresponds to a water loss of ~10 tons/(ton pulp). Because the discharged water contains many deinking chemicals, such as surfactant and basic materials, reducing water removal is also important for a deinking mill. The result of this study indicates that properly controlling the froth height and froth stability is a cost-effective method to reduce both water consumption and fiber loss.

Effect of flotation time on the true flotation and physical entrapment

Fig. 7 shows the effect of flotation time on the total fiber loss and water loss. It can be seen that the intercept of the plot of fiber loss against water loss is increased as the flotation time is increased, which suggests an increase in the true flotation. This is reasonable because the more air bubbles injected into the pulp, the higher the probability of fiber adhering onto the air bubbles. **Fig. 7** also indicates that although the intercepts for 7- and 2-minute flotation were different, the same slope of fiber loss against water loss was obtained. This suggests that the rate of removal of washable entrapped fibers is not a function of total water loss or flotation time. This agrees well with **Equation (2)** in which the slope C does not depend, but the intercept (A + B) does depend on the total water removal V_{water}. According to **Equation (2)**, the ratio between the intercepts of fiber loss against water removal obtained at 7 and 2 minutes should be 3.5 (=7:2). However, **Fig. 7** indicates this ratio is only about 2. Many factors, such as the decrease in the fiber consistency and surfactant concentration with an increase in flotation time, may cause the difference between experimental data and theoretical prediction.

Fiber consistency in removed froth

Fig. 8 shows the consistency of fibers in the froth as a function of froth height. It can be seen that, in most cases, the consistency of fibers in the froth is lower than the original pulp, regardless of hydrophilic (unsized) or hydrophobic (sized) fibers. This suggests that, for these systems, water is more easily entrapped than fibers in the froth. However, because the entrapment of fibers in the foam network depends on the fiber length and froth structure, it is not clear if this is a general conclusion for other flotation systems.

Effect of air bubble size on the water and fiber losses

Many factors, such as surfactant concentration, gas flow rate, pore size of the air inlet filter, pulp concentration, soluble and colloidal materials in pulp, etc., may affect bubble size. Qualitative results showed that both fiber loss and ink removal are air bubble size-dependent. For example, when a 2-μm filter was used, some very small air bubbles were adsorbed onto the fiber surface, which resulted in fibers floating to the top of the flotation cell after the flotation experiment. This phenomenon was significant only when sized fibers were used. When unsized furnish or a 10-μm filter was used, the fibers sank to the bottom after the flotation experiment.

A typical example of bubble size effect on the total fiber loss is given in **Fig. 9**. As discussed before, the small bubbles gave higher water loss compared to the large bubbles. At a froth height of 7 cm, air flow rate of 1500 ml/min, 100 mg/L TX-100, and 0.45% unsized bleached softwood fibers, the water loss was 330 and 140 ml/min when 2- and 10-μm air filters were used, respectively. Because the water loss is significantly higher for the 2-μm air filter than for the 10-μm air filter, a higher fiber loss was obtained at the same flotation time.

Effect of calcium ion on the fiber loss

Although many researchers indicated that calcium ions will affect both the ink removal and fiber loss, the results obtained in previous studies did not agree with each other. **Fig. 10** shows the effect of calcium ions on fiber loss when TX-100 was used as a surfactant. It was found in our study that calcium ions have no significant effect on the foam stability when TX-100 was used, but it really increases the fiber loss. Furthermore, our experimental results also indicated that the calcium ions will increase water removal when other parameters remain the same. The reason for the effect of calcium ions on the fiber loss is not clear.

Conclutions

1. The fiber loss in the flotation process is attributed to two different mechanisms: fiber-bubble adhesion and froth entrapment, but the fiber adhesion is less important compared with the physical entrapment.

2. The fraction of true flotation in total fiber loss increased as the hydrophobicity of fibers increased. For very hydrophobic fibers (0.6% AKD sized bleached softwood fibers), the true flotation fraction was in the range of 25-33% base on total removed fibers under our experimental conditions.

3. The froth structure and air bubble size will significantly affect the fiber loss. Small bubbles lead to higher water and fiber losses.

4. The increase in the froth height will lead to a decrease in water loss and fiber loss. However, only part of the entrapped fibers can be washed back to the pulp suspension during water drainage.

Literature

Ajersch, M., and Pelton, R., (1993): The growth of bubbles on pulp fibers and on carbon black dispersed in supersaturated carbon dioxide solution, 2nd Research Forum on Recycling, Montreal, Canada, 129.

Ajersch, M., and Pelton, R., (1996): Mechanisms of pulp loss in flotation deinking, J. Pulp and Paper Sci., 22:9, 338.

Ajersch, M., Pelton, R., Loewen, S., and Chan, A., (1992): Measurement of dispersed air in newsprint pulp suspensions, Tappi J., 75:2, 125.

Deng, Y., and Abazeri, M., Wettability of wood fiber in surfactant and polymer solutions, Submitted to the Engineering Foundation Conference, Hawaii, January, 1998.

Dorris, G., and Page, M., (1997): Deinking of toner-printed papers. Part I: Flotation kinetics, froth stability and fibre entrainment, J. Paper Pulp Sci., 23:5, 206.

Li, M. and Muvundamina, M., (1994): Fractionation of recycled pulp obtained from mixed paper, 1994 TAPPI Recycling Symp., Atlanta, TAPPI Press, 303.

Li, M. and Muvundamina, M., (1995): Fractionation of fiber slurries via froth flotation and sedimentation, Prog. Pap. Recycling, 4:3, 32.

Turvey, R. (1993): Why do fibers float, J. Pulp Paper Sci., 19:2, 52.

Turvey, R., (1987): Stock loss as a function of water hardness in flotation deinking, Paper Techn. and Ind., 28:1, 366.

Warren, L., (1985): Determination of the contributions of true flotation and entrapment in batch flotation tests, Int. J. Min. Proc. 14, 34.

Table 1. *Properties of fibers used in this study. The receding contact angle for all of the fibers (sized and unsized) in water and surfactant solutions is zero.*

Fibers	Average fiber length (mm)	Weight of AKD (based on dry fiber weight)	Advancing contact angle in water (degree)	Advancing contact angle in 100-mg/L TX-100 solution (degree)
Unsized	2.83	non	18	<5
0.2% AKD sized	2.83	0.2%	74	28
0.6% AKD sized	2.83	0.6%	102	39

FIGURE CAPTIONS

Fig. 1. *Schematic diagram of the graduated cylinder flotation apparatus.*

Fig. 2. *The water loss as a function of froth height obtained using different air filters. TX-100: 100 mg/L; flow rate: 1800 cm^3/min; flow time: 2 minutes; no fibers.*

Fig. 3. *Water loss as a function of TX-100 concentration. Air inlet filter: 10-μm air; flow rate: 1800 cm^3/min; time: 2 minutes; froth height: 5 cm.*

Fig. 4. *Fiber loss as a function of water loss for unsized and AKD sized bleached softwood fibers. The water and fiber losses were measured at different froth heights. Pore size of air inlet filter: 10 μm; fiber consistency: 0.52%; concentration of TX-100: 100 mg/L; air flow rate: 1800 cm^3/min; flotation time: 2 minutes.*

Fig. 5. *True flotation fraction as a function of froth height. The true flotation fraction of unsized fibers is assumed as zero. Pore size of air inlet filter: 10 μm; fiber consistency: 0.52%; concentration of TX-100: 100 mg/L; air flow rate: 1800 cm^3/min; flotation time: 2 minutes.*

Fig. 6. *True flotation fraction F as a function of water loss. The true flotation fraction for unsized bleached softwood fiber is assumed as zero. Pore size of air inlet filter: 10 μm; fiber consistency: 0.52%; concentration of TX-100: 100 mg/L; air flow rate: 1800 cm^3/min; flotation time: 2 minutes.*

Fig. 7. *Fiber loss as a function of water loss obtained at 2 and 7 minutes. Fibers used are 0.45% unbleached softwood fibers (without sizing agent). Pore size of air inlet filter: 10 μm; concentration of TX-100: 100 mg/L; air flow rate: 1500 cm^3/min.*

Fig. 8. *Fiber consistency in the froth as a function of froth height. Dashed line is the original pulp consistency in the flotation cell. Pore size of the air inlet filter: 10*

μm; concentration of TX-100: 100 mg/L; air flow rate: 1800 cm^3/min; flotation time: 2 minutes.

Fig. 9. *The total loss of unsized bleached softwood fibers as a function of water loss. The froth height: 7 cm; TX-100 concentration: 100 mg/L; flow rate: 1500 cm^3/min.*

Fig. 10. *Effect of calcium chloride concentration on fiber loss at different froth heights. Pore size of the air inlet filter: 10 μm; concentration of TX-100: 100 mg/L; air flow rate: 1800 cm^3/min; flotation time: 2 minutes; fibers: 0.52% unsized bleached soft kraft.*

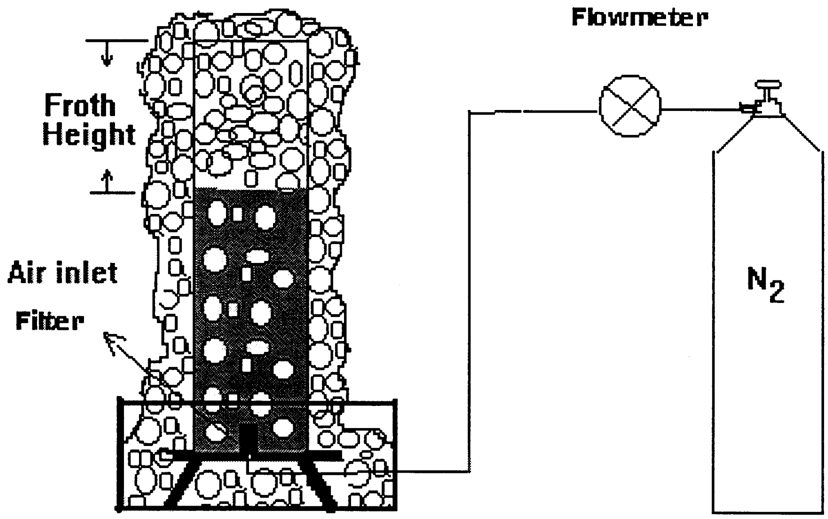

Fig. 1. Schematic diagram of the graduated cylinder flotation apparatus.

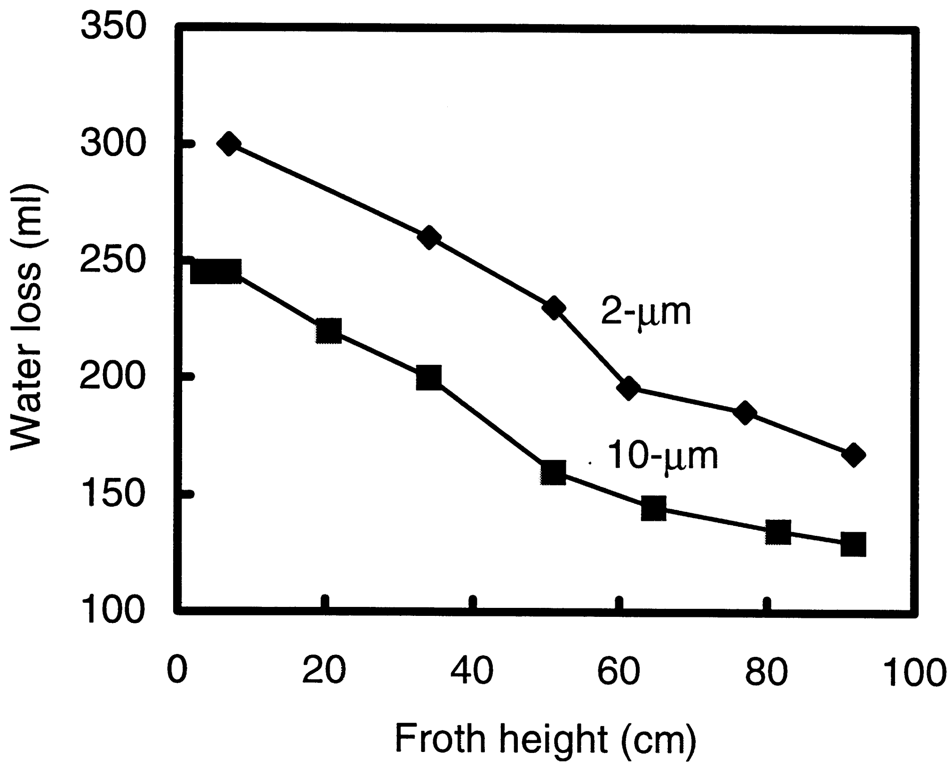

Fig. 2. The water loss as a function of froth height obtained using different air filters. TX-100: 100 mg/L; flow rate: 1800 cm^3/min; flow time: 2 minutes; no fibers.

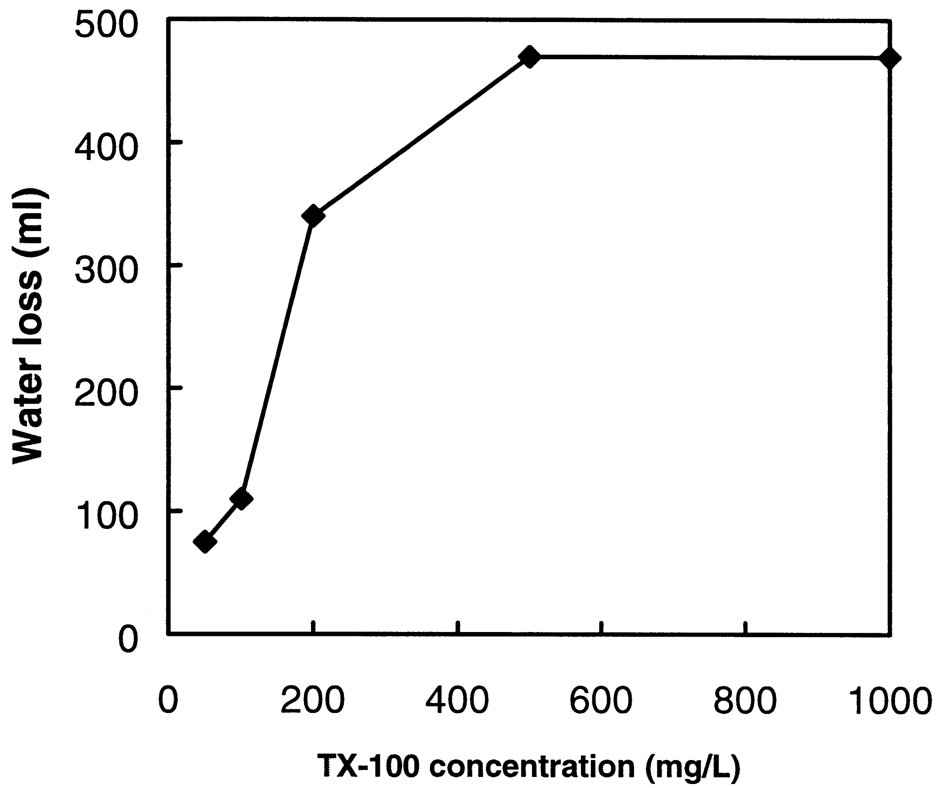

Fig. 3. Water loss as a function of TX-100 concentration. Air inlet filter: 10-μm air; flow rate: 1800 cm^3/min; time: 2 minutes; froth height: 5 cm.

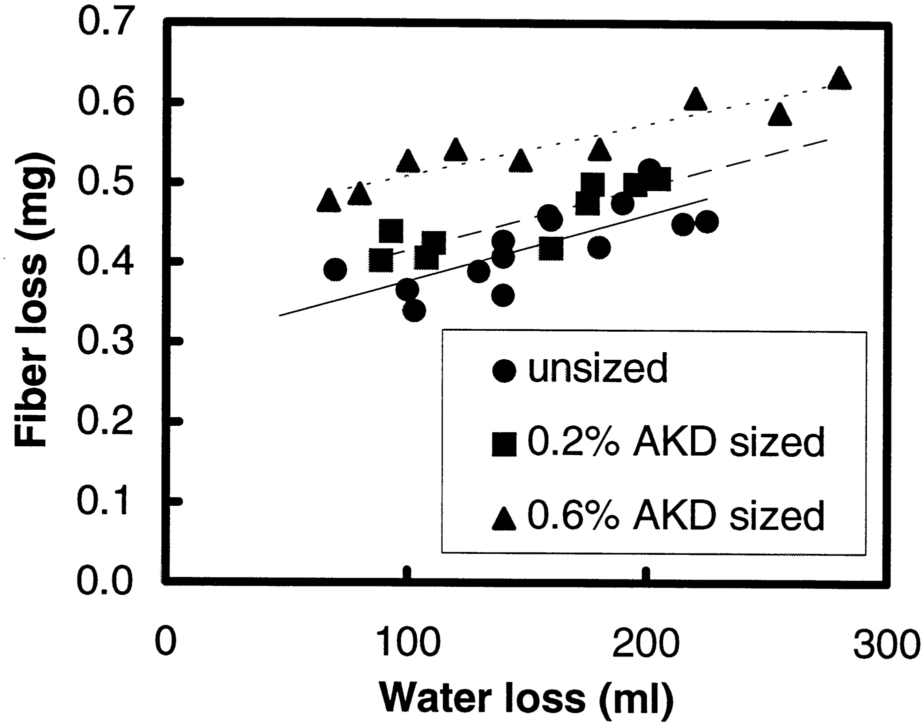

Fig. 4. Fiber loss as a function of water loss for unsized and AKD sized bleached softwood fibers. The water and fiber losses were measured at different froth heights. Pore size of air inlet filter: 10 μm; fiber consistency: 0.52%; concentration of TX-100: 100 mg/L; air flow rate: 1800 cm^3/min; flotation time: 2 minutes.

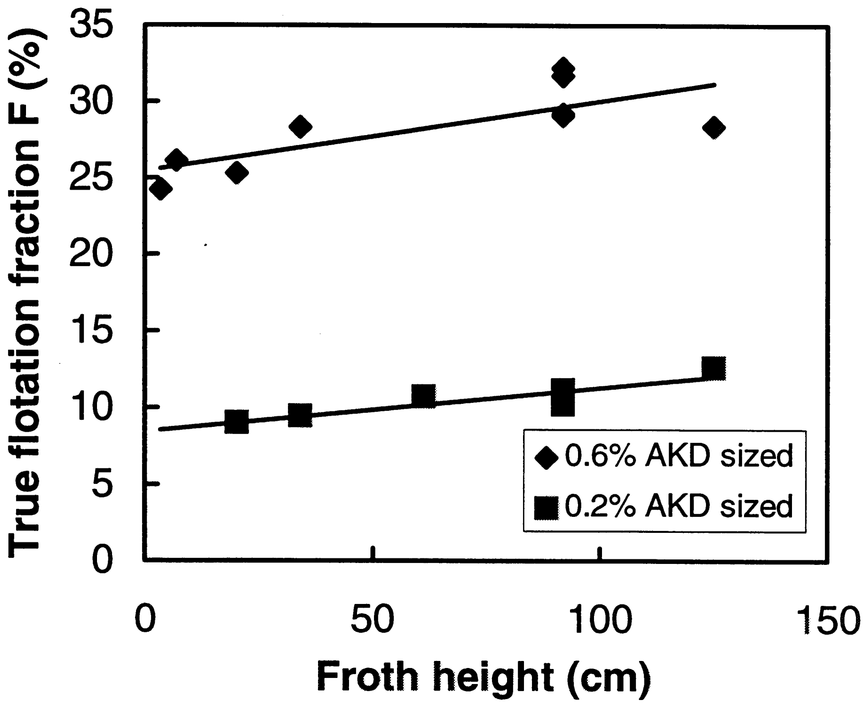

Fig. 5. True flotation fraction as a function of froth height. The true flotation fraction of unsized fibers is assumed as zero. Pore size of air inlet filter: 10 μm; fiber consistency: 0.52%; concentration of TX-100: 100 mg/L; air flow rate: 1800 cm^3/min; flotation time: 2 minutes.

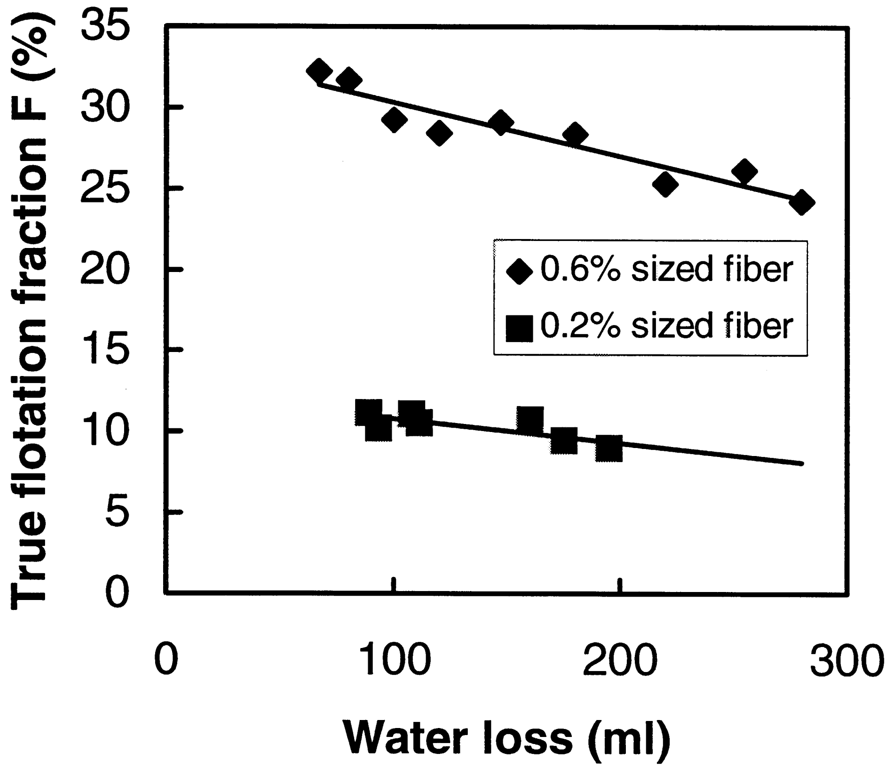

Fig. 6. True flotation fraction F as a function of water loss. The true flotation fraction for unsized bleached softwood fiber is assumed as zero. Pore size of air inlet filter: 10 μm; fiber consistency: 0.52%; concentration of TX-100: 100 mg/L; air flow rate: 1800 cm^3/min; flotation time: 2 minutes.

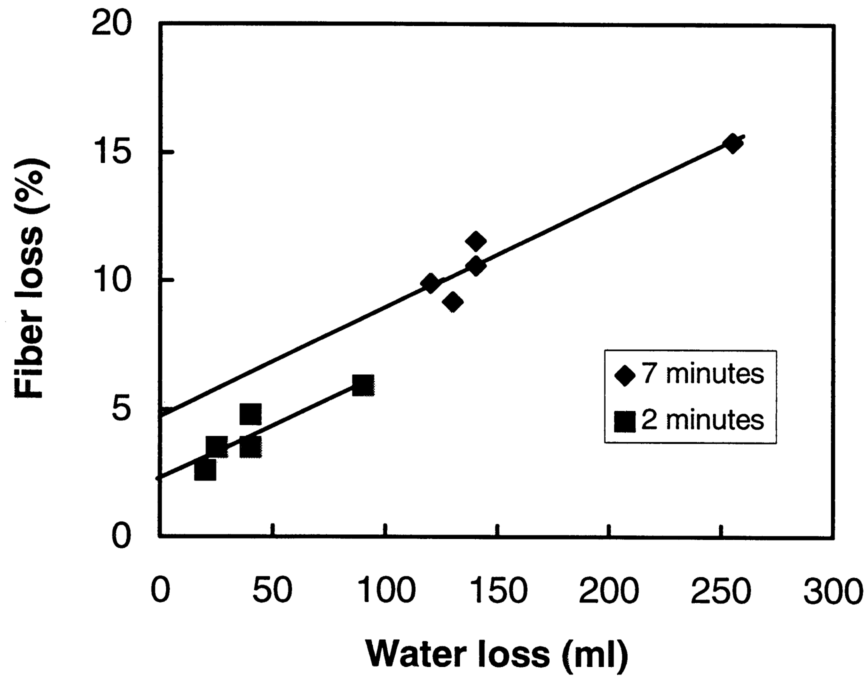

Fig. 7. *Fiber loss as a function of water loss obtained at 2 and 7 minutes. Fibers used are 0.45% unbleached softwood fibers (without sizing agent). Pore size of air inlet filter: 10 μm; concentration of TX-100: 100 mg/L; air flow rate: 1500 cm³/min.*

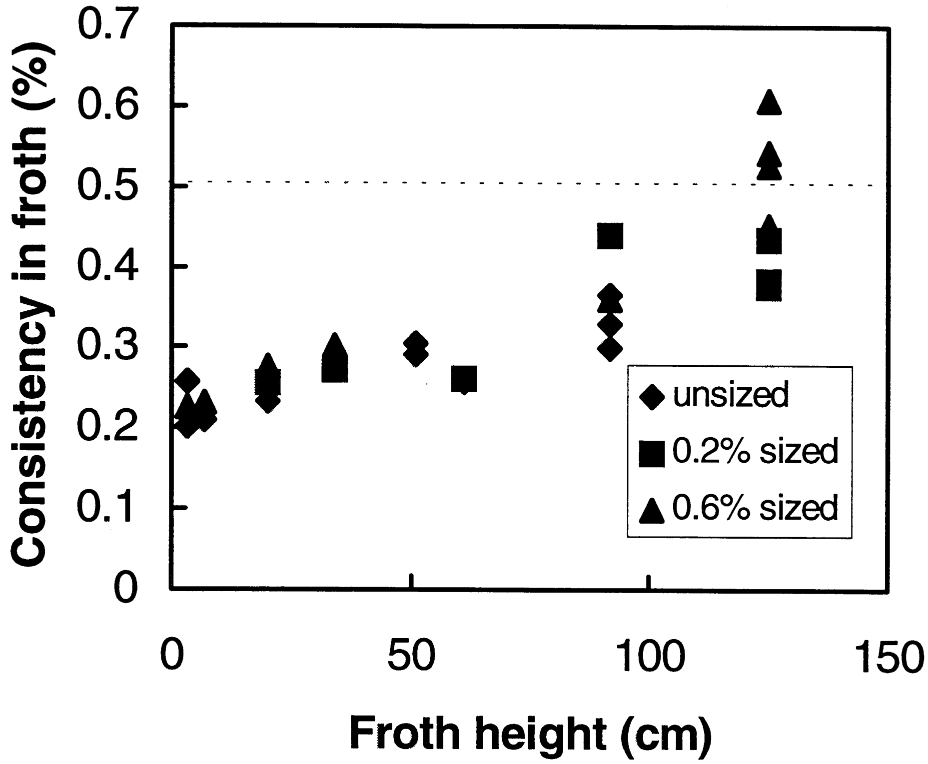

Fig. 8: Fiber consistency in the froth as a function of froth height. Dashed line is the original pulp consistency in the flotation cell. Pore size of the air inlet filter: 10 μm; concentration of TX-100: 100 mg/L; air flow rate: 1800 cm^3/min; flotation time: 2 minutes.

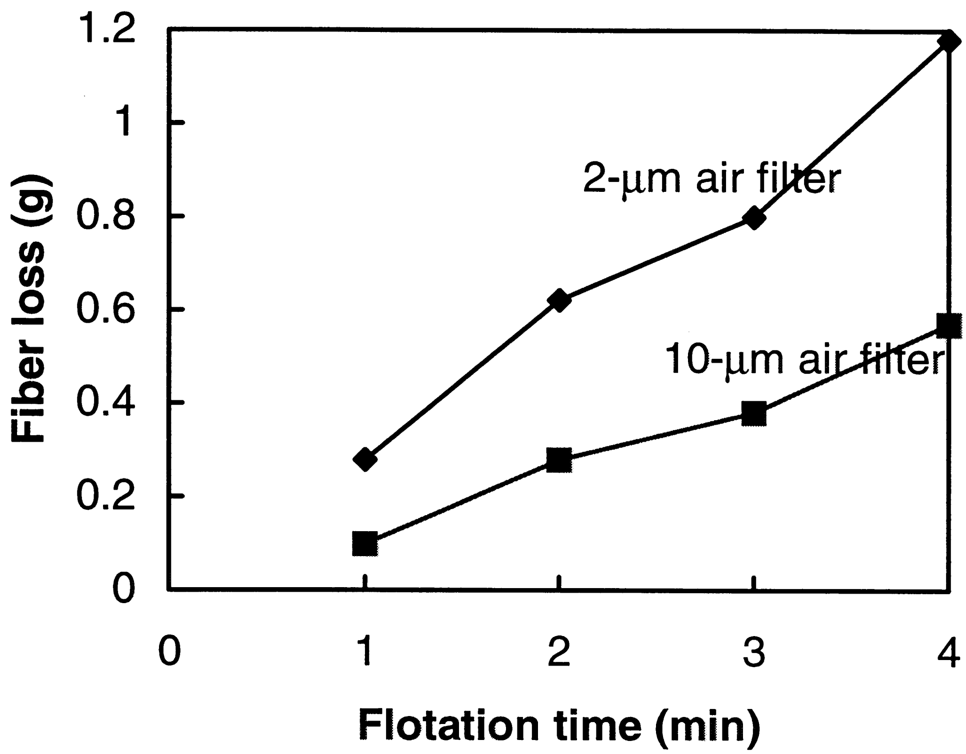

Fig. 9. *The total loss of unsized bleached softwood fibers as a function of water loss. The froth height: 7 cm; TX-100 concentration: 100 mg/L; flow rate: 1500 cm^3/min.*

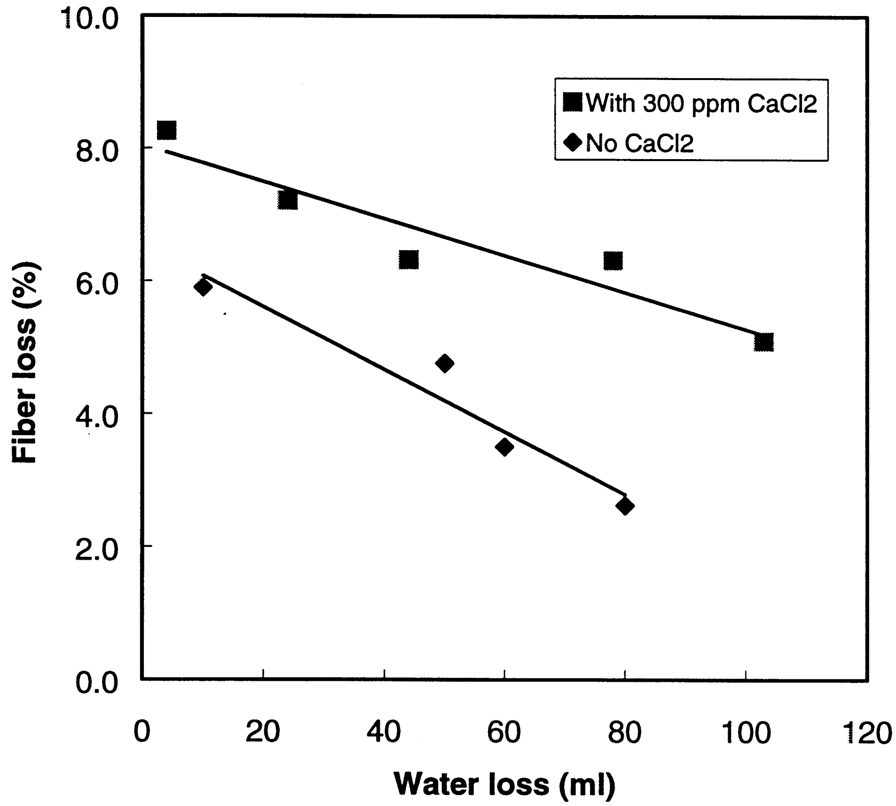

Fig. 10. Effect of calcium chloride concentration on fiber loss at different froth heights. Pore size of the air inlet filter: 10 μm; concentration of TX-100: 100 mg/L; air flow rate: 1800 cm^3/min; flotation time: 2 minutes; fibers: 0.52% unsized bleached soft kraft.